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STELLAR WINDS AND THE EVOLUTION OF LUMINOUS STARS

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ABSTRACT

The effect of a stellar wind on the evolution of stars in the mass range 7–60 $M_{\odot}$ has been investigated for stellar models in which Carson's opacities have been employed. Several cases of mass loss have been considered. It is found that the assumption of heavy mass loss from both blue and red supergiants can account well for the relevant observations of OBN stars, WN stars, and very luminous supergiants of all spectral types. But no amount of mass loss can account adequately for the properties of the B supergiants of lowest luminosity. A critical comparison is made between the present results and some earlier results based on the adoption of Cox-Stewart opacities.

Subject headings: stars: evolution — stars: interiors — stars: mass loss — stars: supergiants — stars: winds

I. INTRODUCTION

The observed pattern of stars at the top of the H-R diagram has not been completely explained by theoretical computations in which a star evolves with constant mass. The observational features that have been most difficult to explain are (1) an apparently unbroken distribution of stars between spectral types O and early A, for $\log(L/L_{\odot}) > 4.5$; (2) a relatively rapid thinning out of the distribution for spectral subtypes later than B3, if $\log(L/L_{\odot}) > 5.3$; and (3) a "gap" at spectral type M for $\log(L/L_{\odot}) > 5.3$.

Among the basic physical assumptions that go into the construction of models of luminous stars, the choice of radiative opacities has turned out to be the most important. If the familiar opacities of Cox and Stewart (1965, 1970) are adopted, then a significant "gap" is predicted to exist on the H-R diagram between the blue main-sequence stars burning core hydrogen and the blue supergiants burning core helium. In this case, it impossible to account for feature 1 mentioned above; nor, as it turns out, can features 2 and 3 be simultaneously explained with the same set of physical assumptions (Stothers and Chin 1976). However, when mass loss is introduced into the models based on Cox-Stewart opacities, some improvement at very high masses is obtained. On the assumption that a substantial fraction of the mass is lost during the early part of the main-sequence phase, features 2 and 3 can be explained (Chiosi and Nasi 1974; de Loore, De Grève, and Lamers 1977; Sreenivasan and Wilson 1978; Chiosi, Nasi, and Sreenivasan 1978). But the difficulty presented by feature 1 is only lessened, not removed.

On the other hand, when the new Carson (1976) opacities are adopted, features 1 and 2 are partially explained without the assumption of any mass loss at all (Stothers and Chin 1977*a*, hereafter Paper V). The principal reason for this difference in results is that the new opacities are very large in the CNO ionization zone under conditions of low density; consequently, the radii of stars with very high masses can become enormously extended even during the phase of core hydrogen burning and thereafter remain so during the phase of core helium burning. But these theoretical models still do not account very well for the blue supergiants with low masses, and they do not account at all for the absence of red supergiants with very high masses. It is our intention in the present paper to investigate whether the adoption of mass loss in the form of a stellar wind in theoretical models based on Carson's opacities can provide an adequate explanation for these two particular observational problems.

In § II, the known mechanisms and rates of mass loss from stars of high luminosity are summarized. Special assumptions needed to calculate the stellar models are noted in § III, and the model results are presented in §§ IV and V. Comparison with the relevant observations is made in § VI. Finally, § VII contains a summary of our main conclusions.

II. MASS-LOSS RATES

Observed rates of mass loss from highly luminous stars are very uncertain; therefore, recourse has often been made to theoretical estimates. At present, the most likely mechanism of mass loss from early-type stars is a radiation-driven stellar wind. But depending on the degree to which the subordinate spectral lines are important in absorbing radiation, the rate of mass loss could be anywhere from insignificant (Lucy and Solomon 1970; Lucy 1975) to quite large (Castor, Abbott, and Klein 1975). Alternatively, if the observed line broadening in early-type supergiants is due to macroturbulence, then the implied acoustic flux could also expel mass at a large rate (Hearn 1975). In either case, theory and observation indicate that the rate of mass loss from early-type stars increases both with luminosity and with radius (for the observations, see, e.g., Hutchings 1976).

Theory further suggests that supergiants of intermediate spectral type and of very high luminosity may develop dynamically unstable atmospheres due to a local density inversion (Peterson 1971; Bisnovatyi-Kogan and Nadezhin 1972; Schmid-Burgk and Scholz 1975). If this instability leads to an outflow of matter, the rate could be as high as $\sim 0.5\ M_\odot\ \mathrm{yr}^{-1}$ (Bisnovatyi-Kogan and Nadezhin 1972). On the other hand, a mild outbreak of convection may well be the only major consequence of the instability (Wentzel 1970; Bisnovatyi-Kogan 1973).

Finally, red supergiants are observed to be losing mass, as a result of some mechanism that is still unidentified but is probably related to the powerful convection and pulsation in the outer envelopes of these stars. Observations indicate that the rate of outflow increases both with luminosity and with radius (Gehrz and Woolf 1971; Sanner 1976; Bernat 1977; Reimers 1977).

Since the measured rates of mass loss from different types of luminous stars are so uncertain, there seems to us to be little point in attempting to do anything more sophisticated than to adopt a simple representation of the mass-loss rate. Accordingly, we have considered four cases for illustration.

Case A.—No mass loss occurs at all.

Case B.—Mass loss occurs continuously in all parts of the H-R diagram at a rate given by (McCrea 1962)

$$-dM/dt = kLR/M\,. \tag{1}$$

(The constant k is expressible in units of $M_\odot\ \mathrm{yr}^{-1}$ if L, R, and M are expressed in solar units.) An adopted value of $k = 1 \times 10^{-11}$ produces rates that are very close to the upper limit of those deduced observationally for both early-type and late-type supergiants. However, there is no reason to expect that either the form of equation (1) or the value of k should be the same for all classes of supergiants.

Case C.—Mass loss is important only among late-type supergiants. In this case, equation (1) is applied whenever $\log T_e < 3.85$, i.e., whenever an extensive outer convection zone exists. Otherwise, the mass-loss rate is taken to be zero.

Case D.—Sudden mass loss occurs at some critical effective temperature that lies in the range of yellow supergiants of very high luminosity. From the work of Bisnovatyi-Kogan and Nadezhin (1972), we adopt a critical effective temperature of $\log T_e = 3.70$, although any other value in the range $4.0 > \log T_e > 3.6$ would probably lead to very similar results because the models without mass loss evolve rapidly (on the envelope Kelvin time) in this range of effective temperature. The initial masses of stars that are subject to this instability in their atmospheres have been determined to be greater than or equal to $20\ M_\odot$ (Bisnovatyi-Kogan and Nadezhin 1972; Schmid-Burgk and Scholz 1975). If $\log T_e \leq 3.70$, the mass-loss rate is here set equal to the highest rate obtainable within the limitations of our computer program ($-dM/dt \approx 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$); otherwise, the rate is set equal to zero.

III. COMPUTATIONAL PROCEDURES

Removal of layers of mass from the stellar models is done by a straightforward computational procedure, described by Kippenhahn and Weigert (1967). If the rate of mass loss is high, the gravitational term $-T\partial S/\partial t$ will no longer be negligible in the outer envelope and should not be set equal to zero there, as is normally done for these layers of the star since they are used to form a simple boundary condition for the deep interior. Therefore, we have not followed Kippenhahn and Weigert in neglecting $-T\partial S/\partial t$ in the outer layers but have adopted Paczyński's (1967) approximation,

$$-T\frac{\partial S}{\partial t} \approx T\frac{\partial M}{\partial t}\frac{\partial S}{\partial M(r)}\bigg|_t\,, \tag{2}$$

which requires no knowledge of the properties of the outer layers of the preceding model. This prescription has worked well for our cases B and C of mass loss. However, in our case D, the decrease of mass turned out to be so rapid that large entropy changes throughout the envelope created numerical problems in matching the envelope and interior solutions; therefore, we were finally obliged to ignore the term $-T\partial S/\partial t$ in the outer envelope for this particular case. Such an omission probably has no significant effect on the derived evolutionary tracks, since the total time during which mass loss occurs in case D is an infinitesimal fraction of the stellar lifetime and since the deep interior structure is found to be not significantly affected by the surface mass loss while the loss is actually in progress.

Our other procedures used in calculating the present stellar models are the same as in Paper V. We have adopted the Schwarzschild criterion for convective instability, although the difference between the Schwarzschild criterion and the Ledoux criterion is actually unimportant here because heavy mass loss suppresses convection in the layers with a gradient of mean molecular weight. In the outer convective envelope, the convective mixing length has been set equal to the pressure scale height ($\alpha_P = 1$). Carson's (1976) radiative opacities have been adopted for $\log T > 3.85$. It should be noted that these opacities have a large bump due to the ultimate ionization of the CNO elements at a temperature of about a million degrees when the density is sufficiently low and that this bump *increases* with decreasing density. Therefore, the more massive stellar models possess extensive convection zones in their envelopes even on the zero-age main sequence; since convection so near the surface is nonadiabatic, the stellar radii are somewhat sensitive to the value of α_P adopted (Stothers 1976).

IV. EVOLUTION AT HIGH MASSES

Initial stellar masses of 15, 30, and 60 $M_\odot$ have been adopted for a zero-age chemical composition of $(X_e, Z_e) = (0.71, 0.04)$. Evolution during the phase of core hydrogen burning has been followed for cases B, C, and D of mass loss. Case A was investigated in

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TABLE 1

EVOLUTIONARY SEQUENCES WITH MASS LOSS FOR STARS OF 15, 30, AND 60 $M_\odot$ INITIALLY*

		CORE HYDROGEN BURNING				CORE HELIUM BURNING			
INITIAL $M/M_\odot$	CASE	τ_H (10^6 yr)	τ_b/τ_H	log T_e (tip)	Final $M/M_\odot$	τ_{He}/τ_H	τ_b/τ_{He}	log T_e (tip)	Final $M/M_\odot$
15..........	A	12.704	1.000	4.23	15.0	0.101	0.000	3.50	15.0
	B	13.255	1.000	4.14	12.7	...	...	...	...
	C	12.704	1.000	4.23	15.0	0.098	0.473	4.64	3.6
30..........	B	5.780	0.960	4.34	9.4	...	...	...	...
	D	5.728	1.000	4.18	12.5	0.107	1.000	4.63	8.0
60..........	B	4.123	0.989	4.33	16.9	...	...	...	...
	C	3.814	0.981	4.09	25.1	...	...	...	...
	D	3.918	1.000	3.95	26.5	0.091	1.000	4.50	23.3

* $k = 1 \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ (cases B and C); τ_b refers to the amount of time spent at log $T_e \gtrsim 3.70$; log T_e (tip) represents the hottest effective temperature achieved by the star during its *leftward* motion in the H-R diagram; $(X_e, Z_e) = (0.71, 0.04)$.

Paper V. Three of the new evolutionary sequences have been extended into the phase of core helium burning (see Table 1).

a) *Case A*

We recall the main results of Paper V. The models of 15 $M_\odot$ were found to burn core hydrogen exclusively in the region of blue giants on the H-R diagram. However, above a certain stellar mass, the evolutionary sequences extended across the whole H-R diagram during the phase of core hydrogen burning, in contrast to the results based on Cox-Stewart opacities. This critical stellar mass was $\sim 20\ M_\odot$ if $Z_e = 0.04$ (or $\sim 30\ M_\odot$ if $Z_e = 0.02$). The subsequent phase of core helium burning took place only in the region of red supergiants, unless the stellar mass was less than $\sim 6\ M_\odot$ if $Z_e = 0.04$ (or less than $\sim 8\ M_\odot$ if $Z_e = 0.02$). However, numerical difficulties prevented us from explicitly following the evolution very far during the red-supergiant phase for masses higher than 20 $M_\odot$ if $Z_e = 0.04$.

b) *Case B*

Certain general inferences can usefully be drawn from a comparison of evolutionary tracks computed with and without mass loss during the phase of core hydrogen burning. For the purposes of discussion, our comparison will be confined to stellar models having the same central hydrogen abundance X_c in sequences that are characterized by the same initial mass. The most important inferences are as follows. First, the surface luminosity is lower when the total mass is reduced. Second, the effective temperature remains nearly unchanged unless $X_c < 0.1$ (in which case the effective temperature is lowered). An exception occurs in the case of an extremely heavy mass loss and will be discussed below. Third, semiconvection is significantly reduced (in our cases entirely suppressed) by the loss of mass. Fourth, the mass fraction contained in the convective core is increased, even though the total core mass itself is smaller. This leads to the whole star's being overluminous for its mass, since a greater fraction of the star is helium-rich and a higher mean molecular weight implies a higher luminosity.

These results are very similar to results that have been obtained previously with different opacities but with comparable mass-loss rates (Tanaka 1966*a*; Chiosi and Nasi 1974; Dearborn and Eggleton 1977; de Loore, De Grève, and Lamers 1977; Sreenivasan and Wilson 1978; Chiosi, Nasi, and Sreenivasan 1978). Such a great similarity leads us to believe that, had we adopted a significantly greater mass-loss rate, we would have found that evolution in the H-R diagram never departs very far from the zero-age main sequence (cf. Tanaka 1966*b*; Hartwick 1967; Simon and Stothers 1970; Chiosi and Nasi 1974).

As it is, our adopted mass-loss rates are about as high as observations seem to permit. Our zero-age main-sequence models lose mass at rates of 7×10^{-8}, 4×10^{-7}, and $2 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ for initial masses of 15, 30, and 60 $M_\odot$, respectively. The influence of such a large rate of mass loss on the evolutionary tracks in the H-R diagram is shown in Figure 1.

The major differences that we have found from earlier work based on Cox-Stewart opacities refer to very high stellar masses. At these masses the new models attain a red-supergiant configuration before central hydrogen exhaustion (as they did in case A). Consequently, the mass-loss rates eventually become extremely high, reaching 6×10^{-5} and $1 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$ for initial stellar masses of 30 and 60 $M_\odot$, respectively. When about 25% of the initial mass has been ejected and hydrogen-processed layers are exposed at the stellar surface, the star begins a shift back into the region of blue supergiants.

The brevity of the red-supergiant phase can be seen in a plot of effective temperature versus central hydrogen abundance, as shown in Figure 2. It is noteworthy that most of the evolution time is spent at log $T_e > 4.1$. The histories of the total stellar mass and of the surface hydrogen abundance are shown in Figures 3 and 4. Because of the high luminosity-to-mass ratio at the time when the star is a blue supergiant, significant amounts of mass are lost even during this phase and the surface appears more and more hydrogen-poor. At the stage of central hydrogen

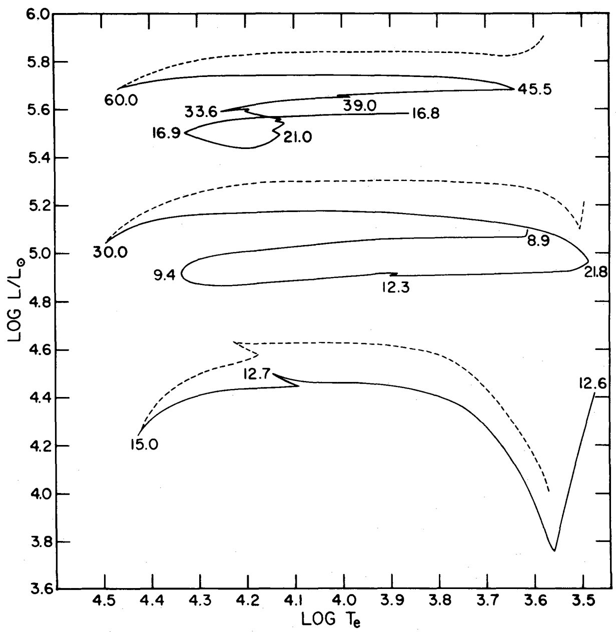

FIG. 1.—H-R diagram showing the evolutionary tracks up to the stage of core helium ignition for case A (*dashed lines*) and for case B (*solid lines*). Except for case A with starting masses of 30 and 60 $M_\odot$, the tracks terminate when log T_c = 8.1. Masses are indicated in solar units.

exhaustion, the star finally attains its highest effective temperature since leaving the region of red supergiants. But very quickly thereafter, the residual hydrogen envelope reexpands. The star becomes red for a second time. In analogy with the somewhat similar final results obtained for case D, we expect that further evolution would lead to the loss of most of the remaining hydrogen envelope, so that the star would end up being very blue and lying near the helium main sequence on the H-R diagram.

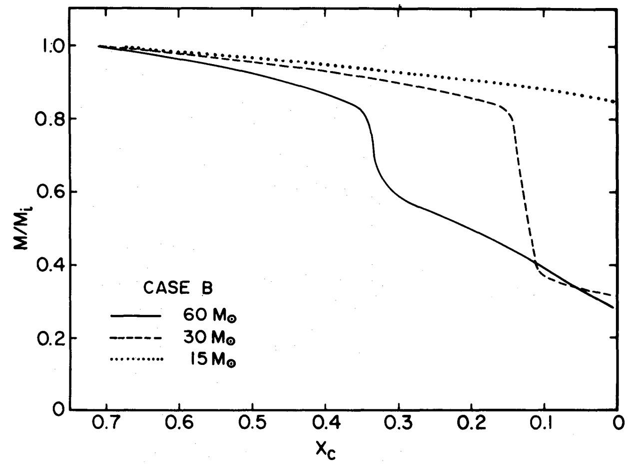

FIG. 3.—Total mass, in units of initial mass, versus central hydrogen abundance for case B.

c) *Case C*

Although numerical difficulties of a nature similar to that of case A developed in the present case for an initial stellar mass of 30 $M_\odot$, they did not develop for 60 $M_\odot$. Therefore, the phase of core hydrogen burning could be completed for the 60 $M_\odot$ sequence and is shown in Figure 5. Apart from a very brief excursion into the region of red supergiants (similar to case B), the evolutionary history resembles rather closely that of case D, which is discussed below.

The situation is very different for a star of 15 $M_\odot$, which completes core hydrogen burning as a blue giant and hence before the loss of any mass. The evolution in the H-R diagram for this case is shown in Figure 6. Unlike the mass-conserving star, which remained in the red-supergiant configuration throughout the phase of core helium burning, the mass-losing star executes a long blue loop, beginning when the star's mass

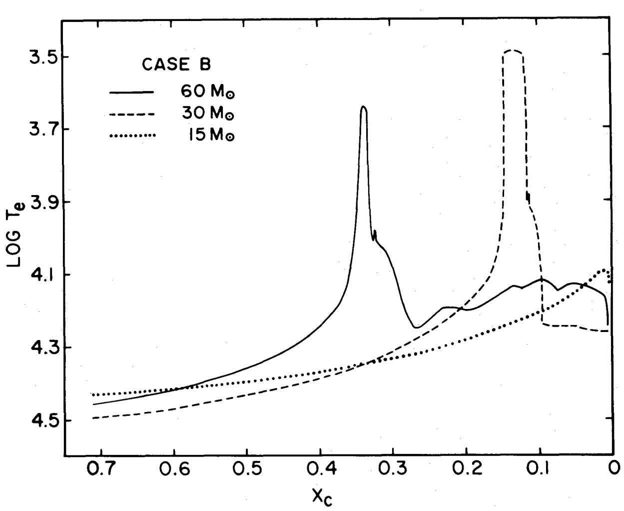

FIG. 2.—Effective temperature versus central hydrogen abundance for case B.

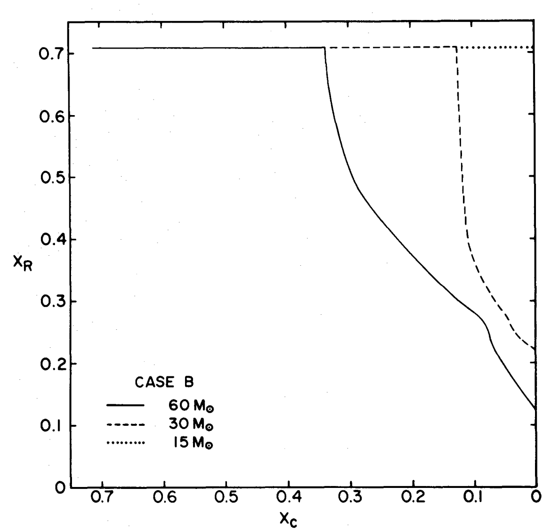

FIG. 4.—Surface hydrogen abundance versus central hydrogen abundance for case B.

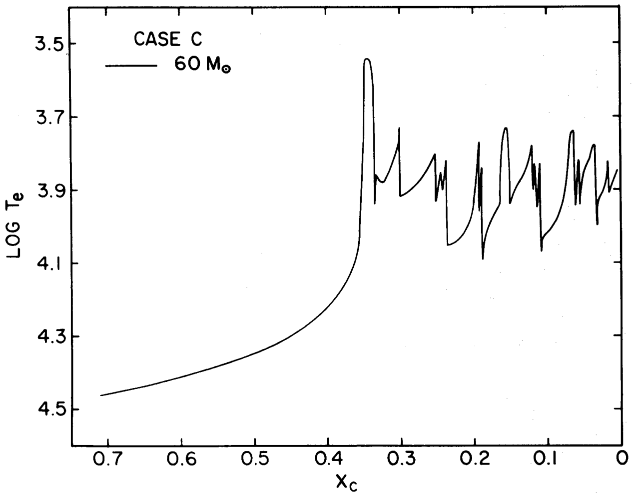

FIG. 5.—Effective temperature versus central hydrogen abundance for case C.

has dropped by about 75% and its central helium content has reached $Y_c = 0.40$. Although extensive envelope convection at the top of the red-supergiant branch has already penetrated into the hydrogen-processed layers and has transported to the surface a small amount of helium-enriched material, it is only the direct exposure of the hydrogen-processed layers (achieved by removal of most of the hydrogen envelope) that leads to the formation of the blue loop on the H-R diagram.

Crossing rapidly over to the blue side of the H-R diagram, the star ends up with a mass of 3.6 $M_\odot$, of which the outer 5% still contains some hydrogen. This residual hydrogen envelope has $X_R = 0.36$, and the partially depleted helium core has $Y_c = 0.38$. These properties cause the star to lie slightly to the right of the helium main sequence on the H-R diagram (cf. Stothers and Chin 1977*b*). A rather similar result has been derived by Chiosi, Nasi, and Sreenivasan (1978) for an evolutionary sequence based on Cox-Stewart opacities with an initial mass of 20 $M_\odot$ but with a higher rate of mass loss. However, the final effective temperature in their case is somewhat cooler than in ours, since their stellar envelope is characterized by a larger integrated hydrogen content.

d) *Case D*

Sudden mass loss, occurring when $\log T_e = 3.70$, causes stellar models of initially 30 and 60 $M_\odot$ to execute numerous blue loops on the H-R diagram. The leftward motion along one of these loops is always found to be very rapid; the rightward motion is, however, usually on the nuclear time scale. Only the loops that are relatively long-lived and penetrate beyond an unstable border area ($3.77 < \log T_e < 3.63$) are shown in Figures 6 and 7. Much of the

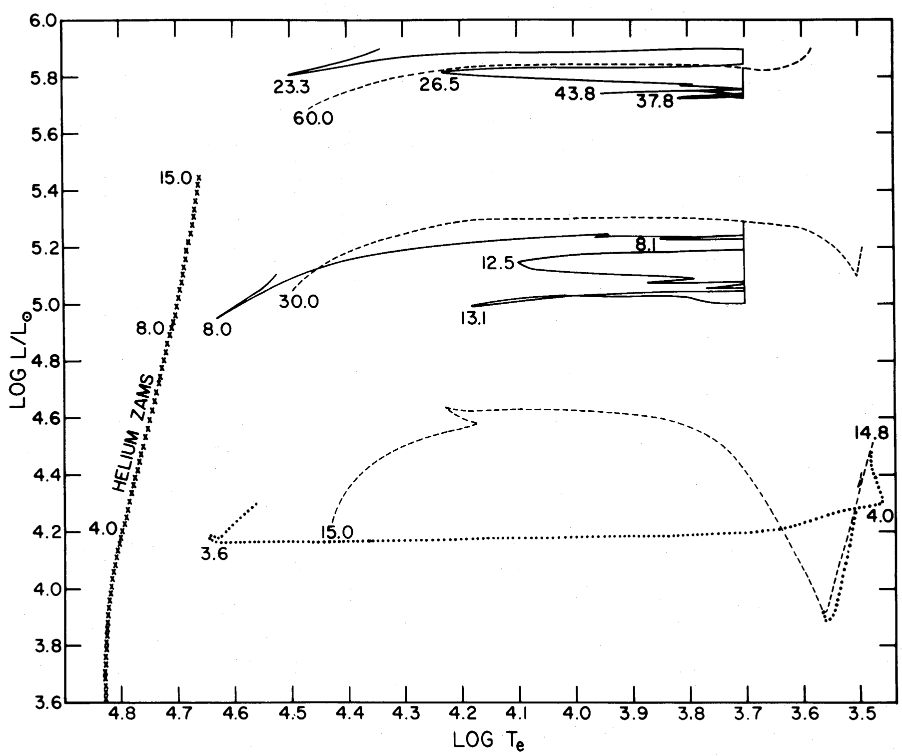

FIG. 6.—H-R diagram showing the evolutionary tracks up to the stage of core helium exhaustion for case A (*dashed lines*), case C (*dotted lines*), and case *D* (*solid lines*). Except for case A with starting masses of 30 and 60 $M_\odot$, the tracks terminate when $Y_c = 0.1$. Evolutionary loops for case D in the unstable border area ($3.77 < \log T_e < 3.63$) are omitted. The helium main sequence is shown for reference. Masses are indicated in solar units.

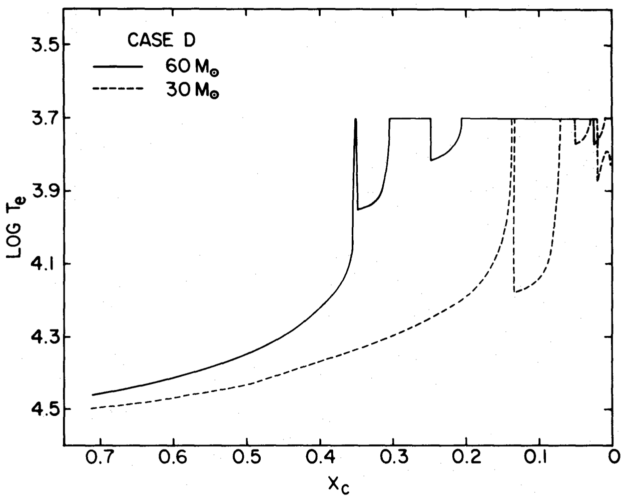

FIG. 7.—Effective temperature versus central hydrogen abundance for case D. Evolutionary fluctuations in the unstable border area ($3.77 < \log T_e < 3.63$) are suppressed.

evolution time is actually spent within this critical border area, which thus forms a "yellow-supergiant branch" on the H-R diagram. Such behavior is in marked contrast to case B, where the star spends much more time as a blue supergiant than as a yellow (or red) supergiant.

The numerous oscillations in effective temperature can be attributed to four competing factors. First, depletion of core hydrogen always increases the central condensation of the star and so increases the stellar radius. Second, mass loss leads to a more nearly chemically homogeneous state of the interior and hence to a smaller radius. Third, mass loss increases the luminosity-to-mass ratio in the envelope and therefore lowers the local densities and raises the local CNO opacities—both of these effects increase the stellar radius. Fourth, multiple solutions of the basic structure equations seem to exist for models of these stars (as for the models in Paper V). Since mass loss is less extreme in case D as compared with case B, chemical homogeneity is a less important factor in the former case, and the star generally succeeds in keeping its radius expanded.

When hydrogen burning finally ceases in the center of the star, gravitational contraction of the core rapidly raises the central condensation. The star approaches the yellow-supergiant branch again, whereupon mass loss recommences. Shortly after the onset of core helium burning, the star moves rapidly to a very blue configuration on the H-R diagram, near the helium main sequence. For our present models with initial masses of 30 and 60 $M_\odot$, respectively, the bluest models have the following characteristics: total mass, 8.0 and 23.3 $M_\odot$; mass of the residual hydrogen envelope, 10% and 13% of the total mass; surface hydrogen abundance X_R, 0.13 and 0.06; and central helium abundance Y_c, 0.81 and 0.71.

V. EVOLUTION AT INTERMEDIATE MASSES

As representative of intermediate stellar masses, we have chosen 7 $M_\odot$. Case A has already been discussed in Paper V. Since a "blue loop" was found to occur during the phase of core helium burning for an initial metals abundance of $Z_e = 0.02$, while it did not occur for $Z_e = 0.04$, we shall here adopt $(X_e, Z_e) = (0.73, 0.02)$ in order to determine how much mass must be lost in order to suppress the "blue loop." Case C alone will be considered, as being solely relevant at 7 $M_\odot$.

It is clear from Table 2 that mass loss at a rate given by $k = 1 \times 10^{-11}$ will suppress the "blue loop." This corresponds to a loss of only a little over 10% of the initial mass. A similar minimum percentage has been derived for models based on the Cox-Stewart opacities in the initial mass range 5–15 $M_\odot$ (Lauterborn, Refsdal, and Weigert 1971; Siquig and Sonneborn 1976; Sreenivasan and Wilson 1978). The similarity between their results and ours is not surprising, as the two sets of opacities do not differ from each other very much for the mild density conditions that prevail in stars of intermediate mass.

A much larger rate of mass loss would remove the entire hydrogen envelope from the star. In our example with $k = 10 \times 10^{-11}$, a stellar remnant of only 1.1 $M_\odot$ is left. In this case the star assumes a new position near the helium main sequence on the H-R diagram. In order to produce a "blue loop" of this special type, about 80% of the initial mass must be lost (cf. our similar results for 15 $M_\odot$ with $k = 1 \times 10^{-11}$). Forbes (1968) and Lauterborn, Refsdal, and Weigert (1971) have also determined about the same requisite percentage for models of 5 $M_\odot$ constructed with Cox-Stewart opacities. A mathematical explanation of the critical percentages has been presented by the latter authors.

Observationally, many evolved stars belonging to the intermediate-mass range show evidence that they have entered into a more or less *normal* "blue loop" phase (Carson and Stothers 1976). From our results we may set a limit of $k \leq 0.8 \times 10^{-11}$ for at least these particular stars. Carson's opacities also require that these stars have $Z_e \leq 0.03$.

TABLE 2

EVOLUTIONARY SEQUENCES WITH MASS LOSS (CASE C) FOR STARS OF 7 $M_\odot$ INITIALLY*

k (10^{11} $M_\odot$ yr^{-1})	τ_{He}/τ_H	τ_b/τ_{He} (loop)	$\log T_e$ (tip)	$M/M_\odot$ (tip)
0	0.156	0.434	4.01	7.0
0.5	0.219	0.453	3.97	6.6
0.7	0.235	0.394	3.93	6.3
1.0	0.251	0.000	3.60	6.0
2.0	0.241	0.000	3.59	5.0
10.0	~0.23	~0.95	~4.6	~1.1

* $\tau_H = 43.69 \times 10^6$ yr; τ_b refers to the amount of time spent at $\log T_e \gtrsim 3.70$ along the blue loop; the maximum effective temperature of the loop is represented by $\log T_e$ (tip); $(X_e, Z_e) = (0.73, 0.02)$.

VI. COMPARISON WITH OBSERVATIONS OF MASSIVE STARS

a) Blue Supergiants

It was noted in Paper V that the faintest observed blue supergiants have luminosities that fall below the theoretical lower limit for stars burning core hydrogen and above the upper limit for stars burning core helium in a "blue loop" phase. Quantitatively, the observed lower limit is $\log (L/L_\odot) \approx 4.5$, while the models burning core hydrogen were all brighter than $\log (L/L_\odot) = 4.8$ and the models burning core helium in a "blue loop" phase were all fainter than $\log (L/L_\odot) = 3.8$, for a mixed population of stars with $Z_e = 0.02$–0.04. If one is unwilling to accept $Z_e > 0.04$, then the theoretical lower limit cannot be lowered any further (unless $\alpha_P < 1$); and if one denies $Z_e < 0.02$, then the theoretical upper limit is also firm. A possible resolution of this impasse is the introduction of mass loss.

We shall first reconsider whether the observed low-luminosity blue supergiants could be burning core hydrogen. It is possible in case B for a star to have an average underluminosity of $\delta \log (L/L_\odot) = 0.4$ with respect to the luminosity that the star would have had if it had evolved without mass loss. For case D (and probably also for case C), an underluminosity of $\delta \log (L/L_\odot) = 0.3$ can be achieved. These underluminosities, if applied to stars whose undisturbed luminosities would have been about $\log (L/L_\odot) = 4.8$, are sufficient to account for the faintest luminosities observed among the blue supergiants. However, in order to obtain models of supergiants burning core hydrogen that are this faint, a high initial metals abundance ($Z_e = 0.04$) is required. This may be acceptable, but in young star clusters containing faint blue supergiants the number of blue supergiants is approximately equal to the number of red ones. This is directly contrary to our model predictions. Moreover, in cases D and C, the predicted effective temperatures for the blue supergiants, at all luminosities where calculations were performed, are much too low as compared with the observed values of $\log T_e = 4.0$–4.2.

A second way of possibly explaining the low-luminosity blue supergiants is to assume that they are in a "blue loop" phase during core helium burning. However, as we have seen, the "blue loop" can be induced only by very heavy mass loss in the preceding evolutionary stages. A serious theoretical consequence of this is that the computed stellar remnants which are burning core helium turn out to be much bluer than the observed blue supergiants (even though the *relative numbers* of blue and red supergiants can be adequately explained if the prior phase of core hydrogen burning has taken place only in the compact blue-giant configuration).

In the case of both alternative explanations, the theoretical models predict that all low-luminosity blue supergiants (and, of course, some high-luminosity ones) should be undermassive for their luminosities by a factor of 2 or 3. Unfortunately, the observational evidence bearing on this point is inconclusive (Stothers 1972; de Loore, De Grève, and Lamers 1977). Furthermore, since interior regions of the theoretical models are exposed that were at one time in the hydrogen-burning core, helium enrichment and nitrogen enrichment (with carbon and oxygen depletion) at the stellar surface are also predicted. The known blue supergiants are worth examining for possible effects of mass loss; the influence of any binary companions would, of course, also have to be taken into account in any such examination.

b) Red Supergiants

A serious problem that was unresolved in Paper V is the observed absence of red supergiants brighter than $\log (L/L_\odot) \approx 5.3$. The only obvious solution to this problem is the introduction of mass loss. However, sudden and devastating mass loss from a yellow supergiant (case D) is not necessary; ordinary red-supergiant mass loss at rates extrapolated from the highest rates observed for less luminous supergiants (case C) seems to be adequate. This result supersedes our earlier conclusion (Stothers and Chin 1970) that the observed rates of mass loss were probably inadequate; our new results are based on the assumption of a very long lifetime (that of core hydrogen burning) for nearly all the very luminous supergiants instead of the short lifetime (that of core helium burning and core carbon burning) that we had envisaged earlier.

It is even possible that an extremely high rate of mass loss from the most luminous supergiants when they are *blue* could prevent them from ever becoming red. However, the rates that we have adopted for case B are about equal to the maximum rates observed, and the stellar models in this case do not avoid the red region.

c) OBN and WN Stars

The assumption of a heavy stellar wind in all of our cases is found to produce within the main-sequence band a number of stellar remnants that should be observed as undermassive, helium-rich, and nitrogen-rich. In the young galactic population, certain helium stars, OBN stars, and WN stars have properties that meet the requirements of our most massive models evolving with mass loss (case B) during the phase of core hydrogen burning. Since our results, which are based on Carson's opacities, are not very different in this respect from previous results based on the Cox-Stewart opacities, we simply refer the reader to the earlier papers for a more detailed discussion (see the references in § IV*b*).

Other WN stars, on the other hand, show less hydrogen at their surfaces and have higher effective temperatures. These objects correspond very closely to our models that are in the phase of core helium burning, for all our cases of very heavy mass loss. A more detailed comparison, based on models of helium stars without hydrogen envelopes, has already been published (Stothers 1976; Stothers and Chin 1977*b*) and therefore will not be repeated here.

VII. CONCLUSIONS

The effect of a stellar wind on the evolution of stars in the mass range 7–60 $M_\odot$ has been investigated for stellar models in which Carson's opacities have been employed. Four cases of mass loss have been distinguished: A, no mass loss at all; B, heavy mass loss from both blue and red supergiants; C, heavy mass loss from red supergiants alone; and D, sudden and catastrophic mass loss from luminous yellow supergiants.

Observational evidence seems to require at least some mass loss from stars initially more massive than $\sim 20\ M_\odot$. As discussed in § I, case A leads to not entirely satisfactory theoretical predictions, regardless of whether the Carson or Cox-Stewart opacities are adopted. Cases C and D, although they have not yet been carried through for the Cox-Stewart opacities, also yield partially unsuccessful predictions if Carson's opacities are used. For both sets of opacities, however, case B can account well for the presence of OBN and WN stars in the main-sequence band in the H-R diagram and for the absence of very luminous M supergiants. Nevertheless, there is no case for which the Cox-Stewart opacities really lead to a satisfactory explanation of either the great width of the main-sequence band at high luminosities or the properties of WN stars with large hydrogen deficiencies, and they require a perhaps unrealistically high rate of main-sequence mass loss in order to explain the paucity of very luminous blue supergiants with spectral types later than B3. On the other hand, Carson's opacities, while solving those problems, nevertheless lead to effective temperatures for the zero-age main sequence that may be too cool (see Stothers 1976) and fail to account satisfactorily for the observations of the blue supergiants of lowest luminosity (at least if standard abundances of the metals are adopted).

The most outstanding feature of the evolutionary sequences based on Carson's opacities is the tendency (induced by the large values of the CNO opacity in the stellar envelope) for the star to expand into the largest configuration possible. In contrast to the sequences based on the Cox-Stewart opacities, the opacity overwhelms all other competing physical factors, including mass loss. Only when the chemical inhomogeneity of the star has been almost totally eliminated does the envelope contract significantly. Therefore, our results are not expected to be greatly dependent on our particular choices of Z_e and of the rate of mass loss. However, *large* changes in these parameters could make a considerable difference. For example, if the blue supergiants of low luminosity do not have binary companions with which they have interacted so as to avoid becoming red supergiants, their existence might be explained by the supposition that they have started with $Z_e < 0.02$, in which case they could be in a "blue loop" phase during core helium burning, or by the supposition that they have started with $Z_e > 0.04$, in which case they could still be burning core hydrogen. Perhaps the occurrence of a wide range of Z_e among the young stars of the greater solar neighborhood is not beyond the limit of observational possibility.

In the interest of ascertaining more precisely the values of Z_e required, we have calculated a few additional evolutionary sequences with $0.005 \leq Z_e \leq 0.04$ and $0 \leq \alpha_P \leq 2$, mass loss being ignored since the relevant luminosities are relatively low. The average luminosity of the faintest observed blue supergiants, $\log (L/L_\odot) \approx 4.5$, can be reproduced during core hydrogen burning with $Z_e \approx 0.08$ (extrapolated) and $\alpha_P = 1$ or, if very small convective mixing lengths are permitted, with $Z_e = 0.04$ and $\alpha_P = 0.1$. Such combinations of Z_e and α_P, however, yield improbably cool zero-age main sequences (see Stothers 1976). Moreover, no combination of Z_e and α_P within the tested ranges leads to a "blue loop" during core helium burning that is brighter than $\log (L/L_\odot) \approx 4.2$. To achieve such a "blue loop," one requires $Z_e < 0.005$ (or, possibly, $\alpha_P > 2$). These constraints on Z_e seem to raise a serious problem for the Carson opacities insofar as the large CNO opacity bump is concerned, unless some other physical ingredient is found to be missing from the present stellar models.

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